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Research on the initial abstraction – storage ratio and its effect on hydrograph simulation at a watershed in Greece

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Abstract

The present research was conducted at an experimental watershed in the prefecture of Attica, Greece, using the selected observed rainfall-runoff events from a four-year time period. The objectives of this study were two: The first was the determination of the initial abstraction I_a – watershed storage S ratio. The average ratio (I_a/S) was equal to 0.014. The corresponding ratio at a subwatershed was 0.037. The difference was attributed to the different spatial distribution of landuses at the extent of the watershed. The second objective of the study was to examine the effect of the SCS empirical equation on hydrograph simulation. This was investigated through the comparison between the observed and two different simulated hydrographs at each one out of eighteen selected storm events. The simulated hydrographs were calculated by applying on the watershed's unit hydrograph two time distributions of excess rainfall that derived from the SCS method using two different approaches. In the first approach, the initial abstraction was determined from the observed rainfall-runoff data, while in the second, it was calculated using the SCS empirical equation. It was found that the SCS empirical equation estimates greater amount of initial abstraction and leads to the delayed start of the excess rainfall and the simulated runoff. This resulted in the overestimation of the peak flow rate and the time to peak at the majority of the storm events.

1 Introduction

A number of methods have been developed for the estimation of direct runoff from storm rainfall. Some of them take into account many hydrological processes that participate in the generation of runoff, while others are not so sophisticated. One of the methods that has been widely used is the SCS method. It was developed for the estimation of runoff for different landuses and soil types.

The relationship between the initial abstraction and the storage of the watershed was examined for the whole watershed, as well as only for the northern subwatershed, for comparison reasons, since the northern part is characterized by different landuses. The basic difference is that there are not impervious areas at the northern part, in contrary to the southern part of the watershed, which is characterized by fast rates of residential development. Thus, the hydrologic response of the northern part is much different compared to that of the southern part and the average ratios (initial abstraction Ia /storage S) that were found for the whole watershed and the northern part were different. It must be noticed that the determined values were close to those found recently from other research studies, like that of Hawkins et al. (2002).

The SCS method was used for the estimation of the time distribution of excess rainfall on a thirty minute time step, at eighteen especially selected observed rainfall-runoff events. The total amount of excess rainfall at each storm event was already known from the separation of observed runoff into direct runoff and baseflow. Thus, the total volume of simulated runoff was always equal to the volume of observed direct runoff. The estimated by the SCS method time distribution of excess rainfall was applied on the unit hydrograph of the watershed for the determination of the simulated hydrograph. Concisely, the procedure for the derivation of the simulated hydrograph at each event was the following; the excess rainfall intensity of the first time interval was multiplied by the values of the unit hydrograph, resulting in a hydrograph. This was repeated for all the excess rainfall time intervals of the storm. Each hydrograph was displaced thirty minutes from the next. The final simulated hydrograph derived, according to the superposition principle, from the horizontal sum of the ordinates of the incremental hydrographs.

The unit hydrograph of the watershed derived from previous research, using observed rainfall-runoff events, as well as the time-area histogram of the watershed, which reflects the incremental areas of the watershed that drain to the outlet during time and was developed by the use of Geographic Information Systems (Dervos et al., 2006). Among other studies that have incorporated a GIS-based time-area unit hydrograph technique are those of Kilgore (1997) and Al-Smadi (1998).

The main objectives of this study were the following:

The determination of the initial abstraction – storage ratio of the watershed.

To examine the effect of the SCS empirical equation on hydrograph simulation. This was investigated through the comparison between observed and simulated hydrographs.

2 Study area

The experimental watershed (Fig. 1) is located at the eastern side of Penteli Mountain, in the prefecture of Attica, Greece. The watershed is characterized by pasture areas, in the place of which a thick pine forest existed in the past, more than ten years ago. Attempts of reforestation are being made during the last years. The vegetation type consists mainly of small bushes. A small percentage of inhabited area (Drafi) is included at the southern part of the watershed. The landuses and the corresponding percentages are shown in Table 1.

The total area of the watershed is 15.18 km^2, its geometric figure is oblong in the North-South direction and the mean, minimum and maximum altitudes are 430, 146 and 950 m, respectively. The steep slopes constitute another characteristic. The mean slope is equal to 21%.

Geologically, the study area consists approximately of 60% schists, 23% conglomerates, 9% marls and 8% marbles. The watershed is divided into two parts, north and south, from the geological point of view. The geologic formations that prevail at the northern part are Schist formations with marble intercalations. There is also a small percentage of Marbles with high water capacity, owing to the numerous fractures that have been extended by the karstic process. A karstic aquifer is located at the northeastern part, at an altitude zone between 500 and 800 m and is distinguished for its great water potential. It has an excellent diet and contributes significantly to the baseflow of the watershed, which is constant throughout the year.

At the southern part of the watershed, there are cohesive conglomeratic formations with varying participation of clay and sand and thus varying infiltration capacity. The

Drafi settlement has been developed on that formation. Additionally, there is a low percentage of impervious marly formations.

The installed equipment consists of two hydrometric stations and a raingauge network that has been operating since October 2003. The raingauge network consists of three gauges that are properly installed in order the complete picture of rainfall to be obtained for the entire watershed. The gauges' records have a ten-minute time step. The first hydrometric station has been operating since January 2003 and is located at the watershed's outlet, where stage-discharge measurements are regularly made. The purpose of these measurements is the derivation of the stage-discharge equation, which is used for the transformation of the stage time series into discharge time series. The stream flow measurements at the outlet are accomplished by using a current flow meter. The second hydrometric station (a spillway construction) has been operating since January 2005. It is installed at the outlet of the northern subwatershed, which constitutes about 51% of the extent of the whole watershed. The water level is recorded at ten-minute intervals at both hydrometric stations.

The length of the main channel is 7456 m and the density of the channel network is 3.72 km/km^2, which implies very good drainage. The baseflow reaches a minimum value (5–15 lt/s) in late summer and a maximum (100–200 lt/s) in spring. The climate at the prefecture of Attica is Mediterranean with a mean annual precipitation of 400 mm and most of the rainfall events occur between October and March.

3 Data analysis

3.1 Selection of storm events

Eighteen storm events were selected based on the following criteria:

Uniform spatial distribution of the rainfall at the extent of the watershed.

Continuous rainfall. Storm events with discontinuous rainfall were excluded.

The antecedent soil moisture conditions to be as high as possible. This means that other storm prior to the selected event should have occurred. Summer storm events were excluded.

The winter events at which snowmelt contributed to runoff were also excluded.

The peak flow rate of the storm event should be higher than 0.2 m^3/s.

The data source was the website: http://www.xbasin.chi.civil.ntua.gr. The analysis time step was thirty minutes. A storm event was considered to be over when there was at least a six-hour period without rainfall. The selected storm events on a rainfall volume ascending order are given in Table 2. The surface rainfall at each event was estimated by the use of the Thiessen Polygon method.

The total excess rainfall Pe in mm was calculated by dividing the total direct runoff volume of each event by the total area of the watershed. The separation of each observed hydrograph into direct runoff and baseflow was based on the hydrograph's points of inflection. These points indicated the starting and the ending point of direct runoff on the rising and recession limb of each hydrograph, correspondingly.

3.2 SCS method

The SCS basic rainfall-runoff equation with the initial abstraction taken into account is the following (SCS, 1972):

$$Pe = \frac{(P - Ia)^2}{(P - Ia) + S} \tag{1}$$

Where:
- P is the total rainfall (mm)
- P_e is the total excess rainfall (mm)
- I_a is the initial abstraction (mm)
- S is the total watershed storage (mm)

The above equation is used when the total rainfall (P) of the storm event is greater than the volume of initial abstraction ($P>I_a$). In the opposite case, the total excess rainfall is equal to zero ($P_e=0$ if $P<I_a$). The initial abstraction (I_a) consists mainly of interception, infiltration and surface storage, all of which occur before runoff begins.

The total watershed storage S includes (I_a). Predominantly, S consists of the infiltration occurring after runoff begins and is controlled by the rate of infiltration at the soil surface or by the rate of transmission in the soil profile or by the water storage capacity of the profile, whichever is the limiting factor (SCS, 1972).

Moreover, the rainfall data that were used for the development of Eq. (1) were totals for one or more storms occurring in a calendar day and nothing was known about the time distributions. The equation therefore excludes time as a variable; this means that rainfall intensity is ignored (SCS, 1972). In addition, Eq. (1) tends to overpredict runoff volume for a discontinuous storm, because it does not account for the recovery of soil storage, caused by infiltration during periods of no rain (Suphunvorranop, 1985). Hjelmfelt (1980b) reports that the SCS method performs better in regions marked by a humid climate if the amount of water retained during runoff is a small fraction of rainfall.

The procedure for the determination of the time distribution of excess rainfall, at each storm event, consists of two basic steps:

Firstly, the total excess rainfall (P_e) of the storm event is determined based on the separation of the observed runoff into direct runoff and baseflow. Then, follows the initial abstraction (I_a), which is equal to the accumulated rainfall from the beginning of the storm to the time when direct runoff starts. The total rainfall (P) of the storm event is known. The only unknown parameter, which is the total watershed storage (S), is calculated using Eq. (1).

Secondly, on a thirty-minute time step, the rainfall values of the storm event are accumulated and tabulated. Then, Eq. (1) is used for the calculation of the accumulated excess rainfall value at each time step. Finally, the increment of excess rainfall at each time step is the difference between the accumulated excess rainfall values at the end and the beginning of the time step (Al-Smadi, 1998).

3.2.1 SCS empirical equation

The SCS empirical Equation that relates the initial abstraction I_a with the total storage S is used in many studies. That is:

$$I_a = 0.2S \tag{2}$$

Equation (2) was derived from records of natural rainfall and runoff from watersheds less than 10 acres in size (one acre is equal to 4046.7 m^2), by plotting I_a versus S for individual storms (SCS, 1972). It is worth mentioning that there was a large amount of scatter in this plotting, mainly because of deficiencies in the accurate estimation of I_a.

Based on recent investigations, Hawkins et al. (2002) suggest changing the coefficient from 0.2 to 0.05. The authors determined the coefficient by two methods for a large number of storms. More than 28 000 storms observed in 307 watersheds located in 24 different eastern states of the United States were used for this purpose. In over 80% of the cases, a value of 0.05 fit the observed rainfall-runoff data better than the original value of 0.2 (Hawkins et al., 2002; Kuntner, 2002).

Substituting I_a from Eq. (2) in Eq. (1), results in the following equation:

$$Pe = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{3}$$

Equation (3) is also used when the total rainfall (P) is greater than the volume of initial abstraction (I_a). (P_e=0 if $P<I_a$). The procedure for the determination of the time distribution of excess rainfall by using Eq. (3) is the same as above, with the difference that the initial abstraction (I_a) is calculated from Eq. (2) and not from the observed data.

3.2.2 SCS infiltration concept

Many questions have arisen regarding the infiltration concept of the SCS method. The SCS method approaches the typical infiltration process, meaning that the estimated losses are greater at the initial time intervals of the storm and they gradually decrease

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towards the final, resulting in increasing amounts of excess rainfall. However, the infiltration model embedded in the SCS method is in disagreement with major infiltration theories, since the infiltration rate during a storm event of constant rainfall intensity decreases and approaches zero instead of a residual constant rate resulting in estimated excess rainfall intensity almost equal to the total rainfall intensity. This predicts the excess rainfall at the very end of a storm of low rainfall intensity (Hjelmfelt, 1980a).

Smith and Eggert (1978) point out two major disagreements of the SCS method with other infiltration theories. The first is that the infiltration, before runoff starts, has a uniform value I_a. Second, according to the SCS method, the infiltration rate, after runoff starts, depends on rainfall rate. In reality, however, the first phase is not a uniform value and the length of it depends on the rainfall rate and patterns, because the surface flux capacity, provided by the soils unsaturated capillary gradient, is larger than the rainfall rate. In the second phase, the rainfall rate surpasses the infiltration capacity and the infiltration rate is controlled only by the condition of the soil (Smith and Eggert, 1978; Brevnova, 2001). Meadows and Chestnut (1983) conclude that the infiltration model embedded in the SCS method performs well only when the rainfall events considered are of short duration without interruptions or for longer lasting periods of rainfall where the soil saturated hydraulic conductivity is not exceeded.

4 Results and discussion

4.1 Determination of the initial abstraction I_a – storage S ratio

The procedure for the determination of the ratio (I_a/S) at each one of the storm events was the following: first, the total excess rainfall (P_e) at each event was estimated from the observed direct runoff. Then, the initial abstraction was determined from the observed rainfall-runoff data. At the next step, the total storage S of the watershed, for that event, was calculated by the use of Eq. (1).

Eighteen storm events were examined and it was found that the average ratio (I_a/S)

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of the watershed is equal to 0.014. The maximum value was 0.037 and the minimum 0.004. More specifically, the results that were calculated for each storm event are shown in Table 3. In this table, the empirical Eq. (2) was taken into account for the calculations in the first three columns, while in the next columns the initial abstraction was determined from the observed rainfall-runoff data.

The ratio $I_a(\text{Emp})/I_a(\text{Obs})$, which shows how many times one is bigger than the other, varied from 1.63 to 9.88 and it increased with the increase in rainfall. The CN was calculated from the following equation:

$$CN = \frac{25400}{S + 254} \tag{4}$$

Where: S is the total storage of the watershed in mm.

The values of I_a and S for each event are plotted in Fig. 2 and the values of the ratio (I_a/S) versus the runoff coefficient at each storm event are plotted in Fig. 3. Figure 2 shows that the initial abstraction, determined from the observed data, is proportional to the total watershed storage at each event, while Fig. 3 shows that the ratio (I_a/S) at most of the events is around 0.01 and is not related to the runoff coefficient.

Additionally, for comparison reasons, a research into the values of the ratio (I_a/S) was conducted at the northern subwatershed. Five storm events were selected based on the same criteria as above, plus the criterion that the rainfall volume of each storm event should be higher than 20 mm, since lower rainfall produces insignificant hydrograph at the outlet of the northern subwatershed.

The selected storm events, which occurred after January 2005, and the results of the analysis are shown in Table 4. The ratio (I_a/S) varied from 0.014 to 0.054 and the average value was 0.037. Despite the fact that more events are necessary for the analysis at the northern part, the determined values indicate a higher ratio.

A comparison between the ratios was also done for the five common storm events and is shown in Table 5. The ratio that was determined at the northern subwatershed is about 3–4 times the ratio of the entire watershed. The calculated CN values for the northern subwatershed and the entire watershed are low, but consistent, approximately equal to 24.

The graph of total rainfall P versus total watershed storage S, at each storm event, is depicted in Fig. 4. The storage S was calculated by Eq. (1) in the first series of points, denoting that the initial abstraction was determined from the observed rainfall-runoff data. The storage S was calculated by Eq. (3) in the second series of points, denoting that the empirical Eq. (2) was taken into account for the calculation of initial abstraction. The graph shows that the rainfall and the storage are proportionally related. Once the rainfall volume increases the total watershed storage also increases. Comparing the estimated values of storage, the values are much greater in the case of use of the observed rainfall-runoff data, leading to lower CN values.

The determined low ratio (I_a/S) and the great storage of the watershed, which increases proportionally to rainfall, are attributed to the combination of the geological and landcover characteristics of the watershed.

The great storage is owed to the special geological structure in combination with the fact that the formations of the whole area are tectonically intensely folded. Schist formations with marble intercalations dominate the northern part of the watershed. They constitute about 85% of the area of this part. These formations are normally impervious when they are at a healthy condition. However, in our case, their upper layer is corroded resulting in the interception of water. Moreover, there are major marble formations, intensely karstic, constituting about 15% of the northern part of the watershed. These formations are characterized by very low runoff coefficient. The southern part of the watershed is more complicated. It consists of a great percentage of impervious areas (residencies, roads), which is constantly increasing due to the high growth rates of the inhabited area of Drafi settlement. Moreover, there are cohesive conglomeratic formations with varying participation of clay and sand and nearly impervious marly formations.

Additionally, the landcover that is dominated by pasture areas (about 88% of the watershed's total area) plays an important role in the retention of rainfall, as well as in the interception of water due to the decrease in the surface water velocity.

The low ratio (I_a/S) of the watershed is mainly attributed to the impervious areas of the southern part. The residencies and the road surfaces of the inhabited area of Drafi constitute areas characterized by high runoff coefficient. The runoff from these areas reaches quickly at the outlet of the watershed, contributing to the quick start of direct runoff, at the early stages of the storm. Thus, the amount of initial abstraction of the watershed is low. The higher ratio (I_a/S) at the northern subwatershed is owed to the lack of impervious areas that implies greater amounts of initial abstraction.

4.2 Effect of the SCS empirical equation on hydrograph simulation

Two simulated hydrographs were calculated for each storm event and resulted from the following process: Firstly, two time distributions of excess rainfall were estimated at each storm event by two different approaches.

Regarding the first approach, which is called SCS(1), the initial abstraction was determined at each storm from the observed rainfall-runoff data, since it is equal to the accumulated rainfall from the beginning of the storm to the time when runoff started. Then, Eq. (1) was used for the estimation of the time distribution of excess rainfall. This time distribution is denoted as "Rainfall Excess 1" in the legend of the rainfall-runoff graphs.

In the second approach, which is called SCS(2), Eq. (2) was used for the calculation of initial abstraction. Then, the excess rainfall time distribution was estimated by Eq. (3). This time distribution is denoted as ''Rainfall Excess 2" in the legend of the rainfall-runoff graphs.

The two estimated time distributions of excess rainfall were applied on the unit hydrograph of the watershed and two different simulated hydrographs were derived. The simulated hydrographs that resulted from the "Rainfall Excess 1" and "Rainfall Excess 2" time distributions are called "Runoff Sim1" and "Runoff Sim2", correspondingly, in the rainfall-runoff graphs. These two simulated hydrographs were compared with the observed hydrograph, at each storm event, focusing on the values of peak flow rate and time to peak flow rate. The time to peak flow rate is defined as the time period from the beginning of rainfall to the time point of peak flow rate.

The observed and the estimated values of peak flow rate, as well as the relative errors in the peak flow rate for all the storm events are shown in Table 6. At 61% of the events the estimations of the SCS(1) method produced negative relative error, while the corresponding percentage for the SCS(2) was 44%. Both of the estimated values from the two methods approached the observed, but the estimations of the SCS(2) method were generally higher than those of the SCS(1) with the exception at three out of the eighteen events.

The absolute relative error in the peak flow rate was calculated for each event and the results were categorized, as shown in Table 7. The average relative error in the peak flow rate, which is the average of the absolute values, was 0.31 for the SCS(1) method versus 0.43 for the SCS(2) method.

Overall, the empirical Eq. (2) overestimated the initial abstraction at each storm event and led to the delay in the beginning of excess rainfall. Therefore, the total excess rainfall at each event had to be allocated in a shorter time period, resulting in overestimated excess rainfall values and consequently, overestimated flow rates.

Regarding the estimations in the time to peak, the estimated values and the relative errors in the time to peak flow rate for all the storm events are shown in Table 8. All the estimated values were greater than the observed. Comparing the estimated values from the two methods, at 39% of the storm events the values estimated by the SCS(2) method were half an hour greater than those estimated by the SCS(1) method. At 17% of the events the differences in the estimations were greater than one hour. At the rest 44% of the storm events the estimated values of the time to peak were exactly the same.

The absolute relative error in the time to peak flow rate was calculated for each storm event and the results were categorized, as shown in Table 9. The average relative error in the time to peak flow rate was 0.067 for the SCS(1) method versus 0.187 for the SCS(2) method. The reason for the greater estimations in the time to peak values from the SCS(2) method is the same as above. The delay in the beginning of excess rainfall due to the greater amounts of initial abstraction that were determined from the empirical equation, results in a short time displacement, towards greater values, of the simulated time to peak.

Regarding the general shape of the hydrographs, at short-duration storm events (Fig. 5 – storm of 1 January 2004, Fig. 6 – storm of 26 February 2005) with great fluctuations in rainfall intensity and more than one peak flow rate, the simulated runoff did not approach satisfactorily the shape of the observed. On the contrary, at long-duration storms, (Fig. 7 – storm of 25 November 2005, Fig. 8 – storm of 31 October 2006, Fig. 9 – storm of 17 February 2007) the simulated hydrographs, especially those of the SCS(1), approached more closely the fluctuations of the observed hydrographs. This is owed to the fact that the initial abstraction exerts a stronger influence on the time distribution of excess rainfall at short-duration events.

Moreover, low-intensity rainfall intervals at the end of some storms (Fig. 10 – storm of 23 November 2005, Fig. 11 – storm of 8 November 2004) produced overestimated flow rates that exceeded the observed. This is owed to the general SCS infiltration concept that estimates greater amounts of excess rainfall as the duration of the storm increases.

5 Conclusions

The low (0.014) average initial abstraction I_a – storage S ratio of the entire watershed is attributed to its great storage in combination with the low amount of initial abstraction. The later is owed to the impervious areas of Drafi settlement, located at the southern part, that contribute to runoff at the early stages of the storm. The storage of the watershed is attributed to its special geological structure, which results in the interception of water, in combination with the great percentage of pasture areas that contribute to the retention of rainfall. The average ratio (I_a/S) is greater (0.037) at the northern subwatershed, due to the lack of impervious areas that generate early runoff. Thus, the initial abstraction is higher, leading to higher (I_a/S) ratio.

The SCS empirical Eq. (2) that was used in the SCS(2) method, consistently overestimated the initial abstraction in all of the storm events. It was approximately 2 to 4 times the one determined from the observed rainfall-runoff data. This resulted in the delayed start of excess rainfall and consequently in the delayed start of the simulated runoff. The total excess rainfall volume at each storm event had to be allocated in a shorter time period, leading to overestimated excess rainfall values and consequently, overestimated peak flow rate in the resulting simulated hydrographs. Regarding the estimated time to peak values, the use of the SCS empirical equation also led to overestimations for the same reason.

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Website of the experimental watershed: http://www.xbasin.chi.civil.ntua.gr.

Table 1. The landuses of the experimental watershed.

Landuse	Area (m^2)	Percentage %
Pasture	10 541 581	70.2
Wood	113 247	0.75
Inhabited area (Drafi)		
1.Residencies	1 118 250	7.37
2.Roads (impervious surface)	502 394	3.3
3.Pasture among residencies	2 791 013	18.38
SUM	15 182 800	100

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Table 2. Selected storm events.

A/A	Storm Event	Rainfall P (mm)	Total Excess Rainfall Pe (mm)	Runoff Coefficient	Rainfall Duration (h)	Peak Flow Rate (m^3/s)
1	6/3/2005	5.60	0.17	3.11%	9.5	0.25
2	24/1/2005	6.53	0.23	3.49%	2.5	0.53
3	26/2/2005	9.59	0.30	3.11%	5.5	0.34
4	29/1/2004	11.22	0.54	4.78%	3.0	0.79
5	1/1/2004	14.26	0.33	2.33%	7.0	0.36
6	15/2/2005	15.23	0.74	4.87%	5.0	1.00
7	23/2/2005	17.05	0.50	2.93%	8.0	1.39
8	8/11/2004	17.26	0.21	1.23%	9.0	0.60
9	17/2/2007	21.09	0.27	1.3%	12	0.49
10	25/12/2003	21.92	0.82	3.75%	6.0	0.87
11	29/12/2004	29.44	1.38	4.68%	11.5	1.97
12	11/2/2007	39.20	1.11	2.84%	11.5	2.36
13	22/3/2007	70.93	4.34	6.12%	17.0	5.10
14	10/10/2006	71.11	3.67	5.17%	10.0	7.26
15	23/11/2005	76.66	6.46	8.43%	16.0	15.09
16	11/1/2004	91.84	7.47	8.14%	32.0	3.06
17	25/11/2005	100.37	18.67	18.60%	33	11.02
18	31/10/2006	117.58	13.41	11.40%	38.0	5.85

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Table 3. Relationship between initial abstraction I_a and storage S of the watershed. The storage S was calculated by Eq. (3) in the first column and then, I_a and CN from S. The storage S was calculated by Eq. (1) in the fifth column, after having determined I_a from the observed data.

	(Empirical)			(Observed)				
Storm Event	S	I_a	CN	I_a	S	CN	I_a/S	I_a(Emp)/ I_a(Obs)
6/3/2005	18.6	3.7	93.2	1.7	84.0	75.2	0.020	2.20
24/1/2005	21.1	4.2	92.3	1.4	110.3	69.7	0.013	3.01
26/2/2005	31.8	6.4	88.9	2.3	170.7	59.8	0.014	2.75
29/1/2004	33.5	6.7	88.3	1.8	154.5	62.2	0.012	3.63
1/1/2004	50.1	10.0	83.5	3.7	325.4	43.8	0.011	2.71
15/2/2005	45.3	9.1	84.9	0.9	261.7	49.3	0.004	9.88
23/2/2005	57.2	11.4	81.6	7.0	191.9	57.0	0.037	1.63
8/11/2004	66.9	13.4	79.1	5.4	652.7	28.0	0.008	2.49
17/2/2007	81.2	16.2	75.8	7.9	622.0	29.0	0.013	2.05
25/12/2003	69.7	13.9	78.5	7.4	243.7	51.0	0.030	1.90
29/12/2004	88.4	17.7	74.2	7.3	334.3	43.2	0.022	2.43
11/2/2007	132.5	26.5	65.7	10.9	693.1	26.8	0.016	2.44
22/3/2007	197.1	39.4	56.3	10.1	791.1	24.3	0.013	3.90
10/10/2006	207.9	41.6	55.0	12.0	892.9	22.1	0.013	3.48
23/11/2005	190.8	38.2	57.1	6.1	699.0	26.7	0.009	6.22
11/1/2004	231.7	46.3	52.3	7.2	874.9	22.5	0.008	6.47
25/11/2005	169.8	34.0	59.9	4.3	398.0	39.0	0.011	7.85
31/10/2006	258.3	51.7	49.6	6.6	807.5	23.9	0.008	7.82

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Table 4. Initial abstraction – storage ratio at the northern subwatershed.

						(Empirical)			(Observed)			
Storm Event	Rainfall P (mm)	Total Excess Rainfall Pe (mm)	Runoff Coeff.	Rainfall Duration (h)	Peak Flow Rate (m^3/s)	S	I_a	CN	I_a	S	CN	I_a/S
22/3/2007	73.5	2.23	3.03%	17	1.45	245.1	49.0	50.9	31.3	759.7	25.1	0.041
10/10/2006	78.4	1.12	1.43%	8	2.05	298.0	59.6	46.0	46.7	867.6	22.6	0.054
23/11/2005	92.2	3.93	4.26%	16	4.05	283.8	56.8	47.2	26.7	1025.3	19.9	0.026
25/11/2005	99.8	10.63	10.65%	32	2.28	225.9	45.2	52.9	9.2	681.5	27.2	0.014
31/10/2006	111.1	5.42	4.88%	38	1.00	329.9	66.0	43.5	42.4	801.2	24.1	0.053

Table 5. Comparison between the ratios (I_a/S) at the northern subwatershed and the entire watershed.

	Northern subwatershed	Entire watershed		Northern subwatershed	Entire watershed
Storm Event	I_a/S (1)	I_a/S (2)	(1)/(2)	CN	CN
22/3/2007	0.041	0.013	3.2	25.1	24.3
10/10/2006	0.054	0.013	4.0	22.6	22.1
23/11/2005	0.026	0.009	3.0	19.9	26.7
25/11/2005	0.014	0.011	1.2	27.2	39.0
31/10/2006	0.053	0.008	6.5	24.1	23.9

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Table 6. Peak flow rate analysis.

	Peak Flow Rate (m^3/s)			Relative Error	
Storm Event	Observed values	Estimated values SCS (1)	Estimated values SCS (2)	SCS (1)	SCS (2)
6/3/2005	0.25	0.37	0.37	0.49	0.47
24/1/2005	0.53	0.494	0.58	–0.07	0.10
26/2/2005	0.34	0.46	0.57	0.36	0.67
29/1/2004	0.79	1.28	1.37	0.62	0.73
1/1/2004	0.36	0.48	0.76	0.34	1.13
15/2/2005	1.00	1.45	1.55	0.44	0.54
23/2/2005	1.39	1.15	1.20	–0.17	–0.13
8/11/2004	0.60	0.48	0.40	–0.21	–0.34
17/2/2007	0.49	0.39	0.58	–0.22	0.18
25/12/2003	0.87	1.19	1.56	0.37	0.80
29/12/2004	1.97	2.48	2.78	0.26	0.41
11/2/2007	2.36	1.66	1.53	–0.29	–0.35
22/3/2007	5.10	3.20	4.85	–0.37	–0.05
10/10/2006	7.26	6.25	6.63	–0.14	–0.09
23/11/2005	15.09	8.04	8.70	–0.47	–0.42
11/1/2004	3.06	1.91	0.70	–0.38	–0.77
25/11/2005	11.02	9.41	12.61	–0.15	0.14
31/10/2006	5.85	4.51	3.70	–0.23	–0.37

Table 7. Absolute relative error in the peak flow rate.

Absolute Relative Error (R.E.) in the Peak Flow Rate	% of the SCS(1) simulated hydrographs	% of the SCS(2) simulated hydrographs
R.E.<0.1	5.6	16.7
0.1<R.E.<0.2	16.7	16.7
0.2<R.E.<0.3	27.8	0
0.3<R.E.<0.4	27.8	16.7
R.E.>0.4	22.2	50

Table 8. Time to peak flow rate analysis.

	Time to Peak Flow Rate (h)			Relative Error	
Storm Event	Observed values	Estimated values SCS (1)	Estimated values SCS (2)	SCS (1)	SCS (2)
6/3/2005	3	3.0	3.5	0.00	0.17
24/1/2005	2.5	2.5	3.0	0.00	0.20
26/2/2005	4	4.5	5.0	0.13	0.25
29/1/2004	3	3.5	3.5	0.17	0.17
1/1/2004	5.5	5.5	6.0	0.00	0.09
15/2/2005	2.5	3.0	3.5	0.20	0.40
23/2/2005	7.5	8.0	8.5	0.07	0.13
8/11/2004	5.5	6.0	6.0	0.09	0.09
17/2/2007	11.5	11.5	12.0	0.00	0.04
25/12/2003	12	12.0	12.0	0.00	0.00
29/12/2004	9	9.5	9.5	0.06	0.06
11/2/2007	9.5	9.0	10.0	–0.05	0.05
22/3/2007	13.5	13.5	13.5	0.00	0.00
10/10/2006	8	9.0	9.0	0.13	0.13
23/11/2005	11	11.5	11.5	0.05	0.05
11/1/2004	11.5	14.5	23.5	0.26	1.04
25/11/2005	29.5	30.0	30.0	0.02	0.02
31/10/2006	22	22.0	32.5	0.00	0.48

Table 9. Absolute relative error in the time to peak flow rate.

Absolute Relative Error (R.E) in the time to peak flow rate	% of the SCS(1) simulated hydrographs	% of the SCS(2) simulated hydrographs
R.E.<0.1	72.2	50
0.1<R.E.<0.2	22.2	27.8
0.2<R.E.<0.3	5.6	5.5
R.E.>0.3	0	16.7

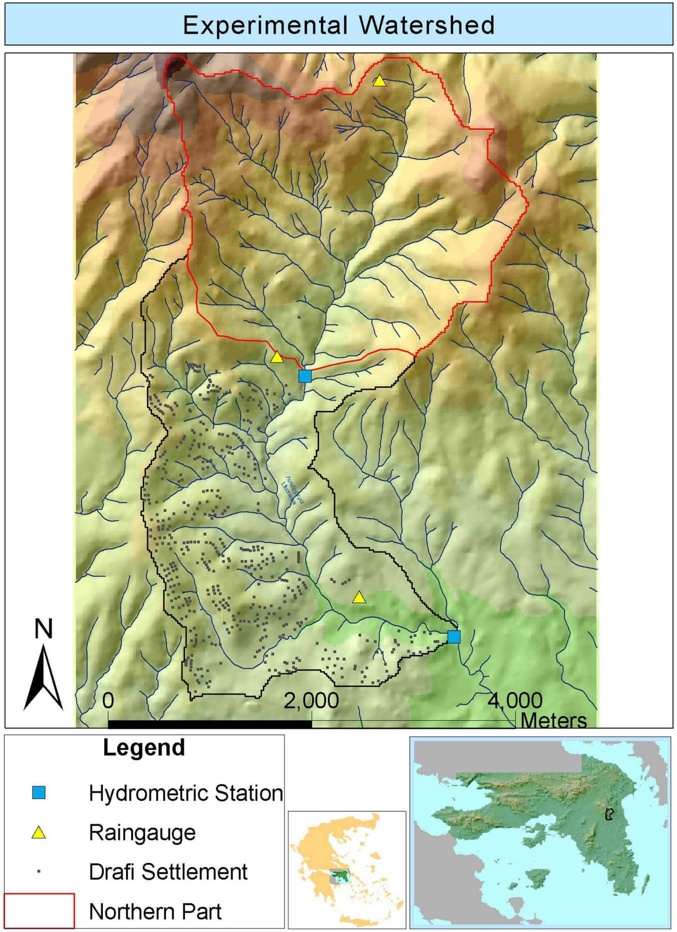

Fig. 1. The study area.

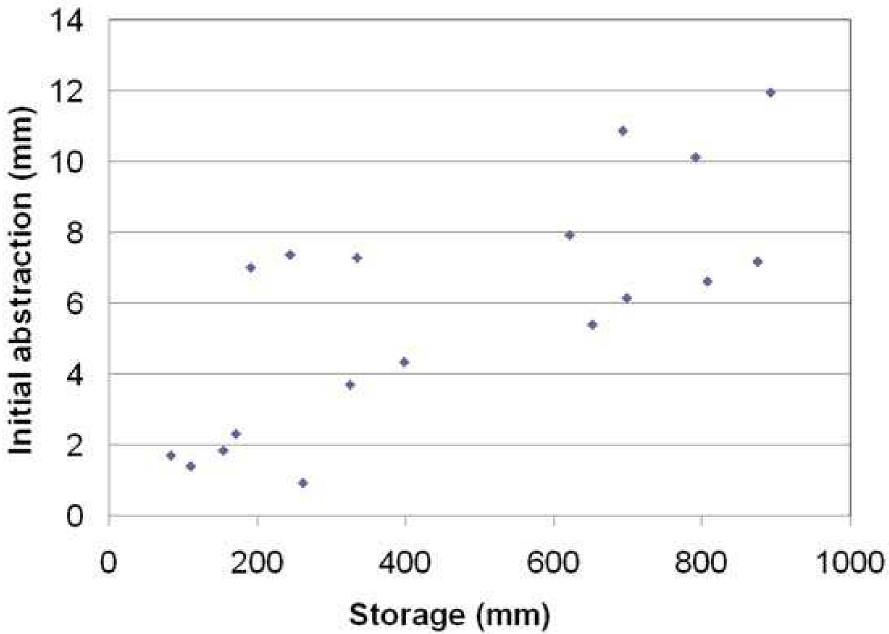

Fig. 2. Graph of initial abstraction I_a versus total watershed storage S, at each event.

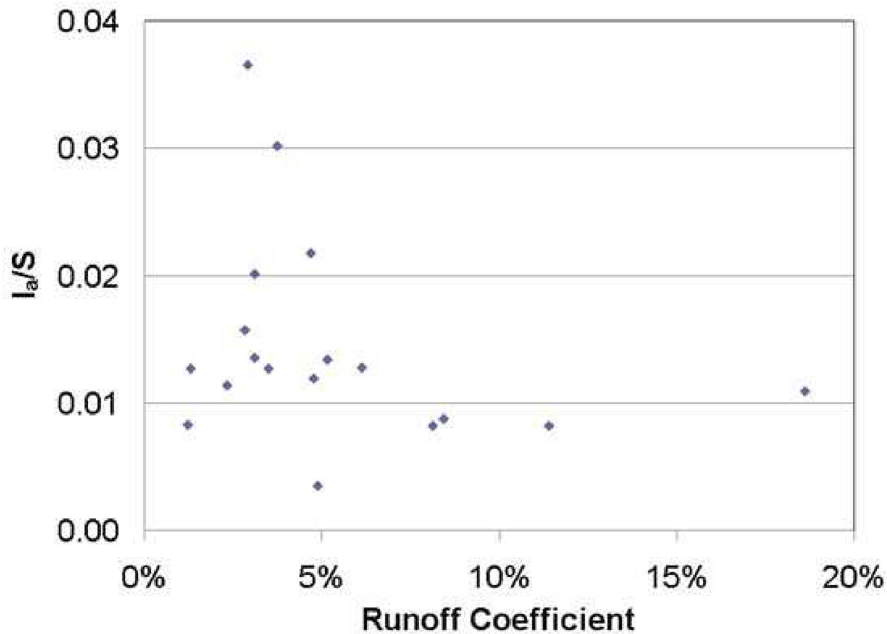

Fig. 3. Graph of the (I_a/S) ratio versus runoff coefficient, at each event.

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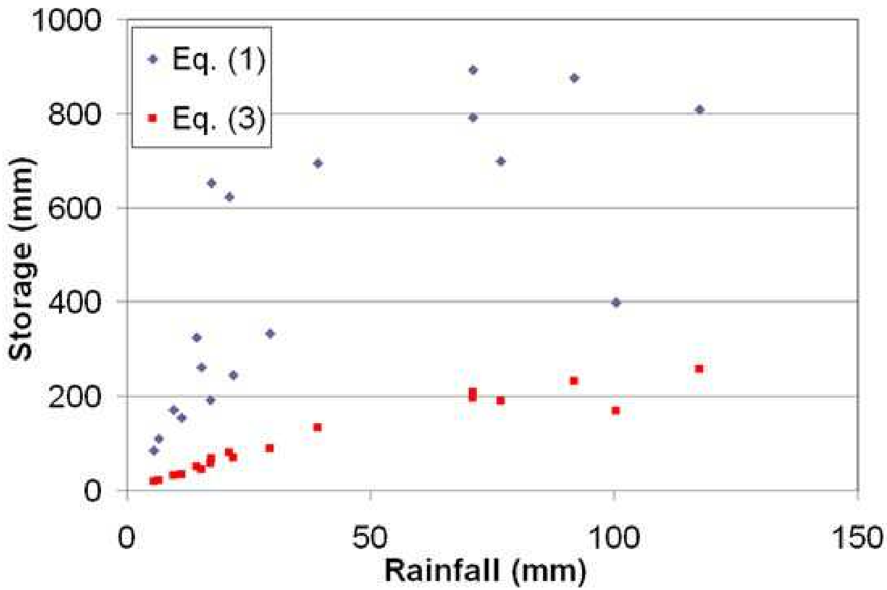

Fig. 4. Graph of total rainfall P versus total watershed storage S, at each storm event. Equation (1) takes into account the observed data for the determination of initial abstraction, while in Eq. (3) the initial abstraction is calculated from the SCS empirical equation.

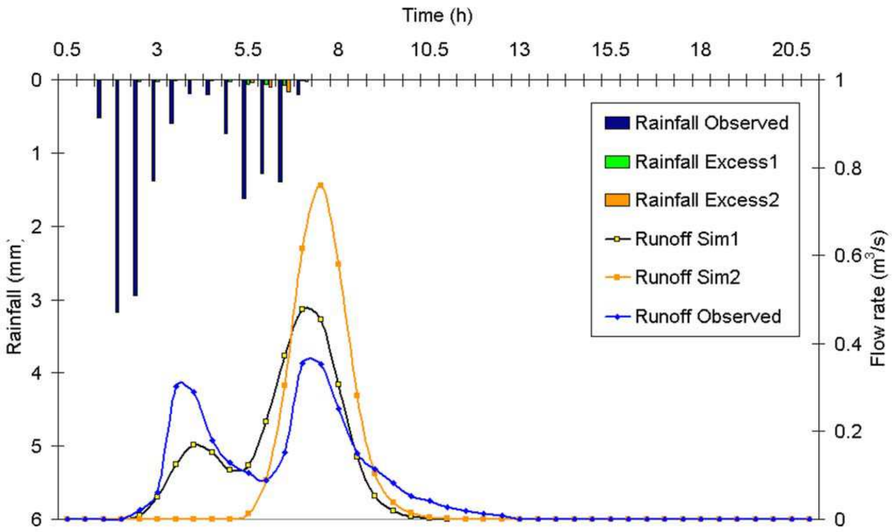

Fig. 5. Storm event of 1 January 2004.

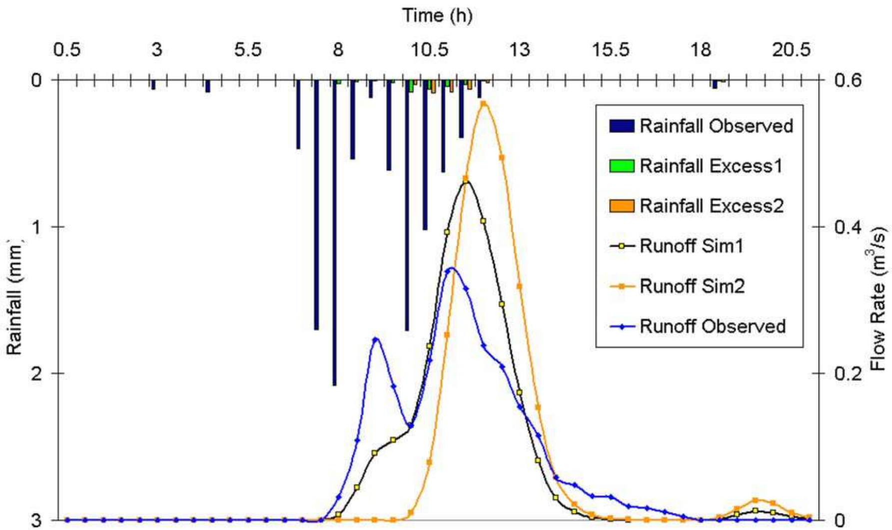

Fig. 6. Storm event of 26 February 2005.

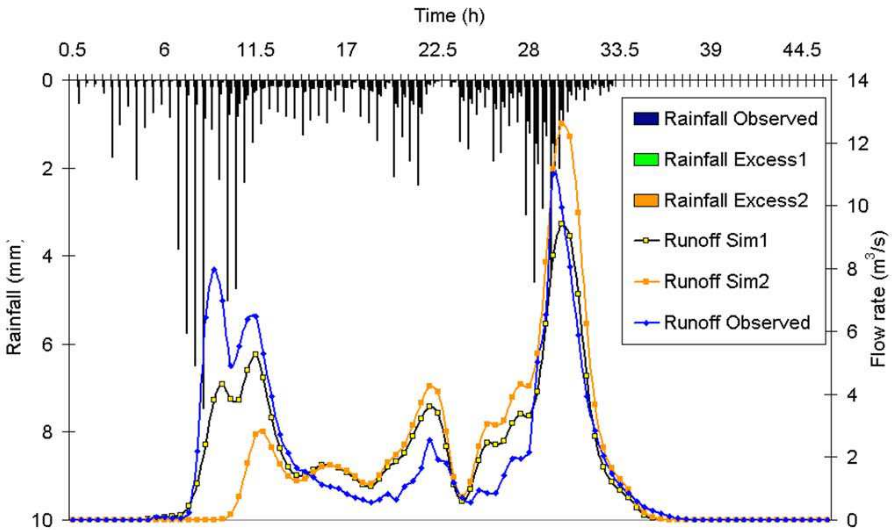

Fig. 7. Storm event of 25 November 2005.

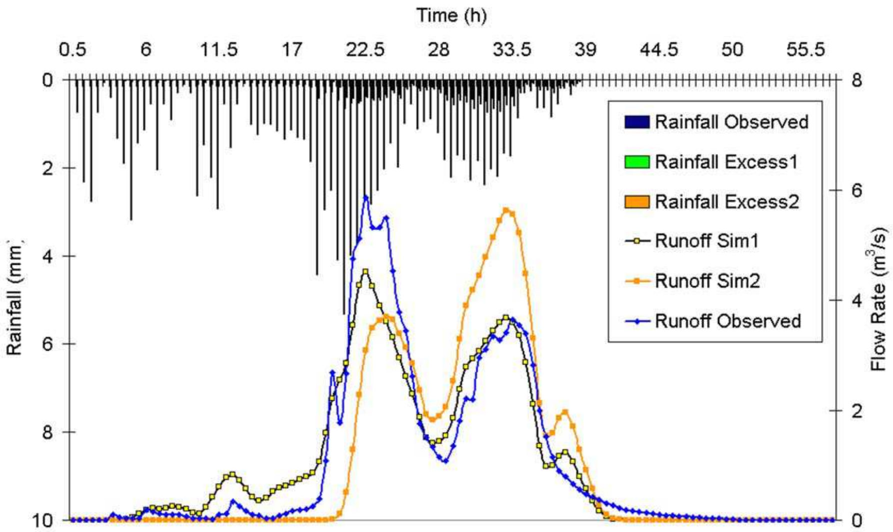

Fig. 8. Storm event of 31 October 2006.

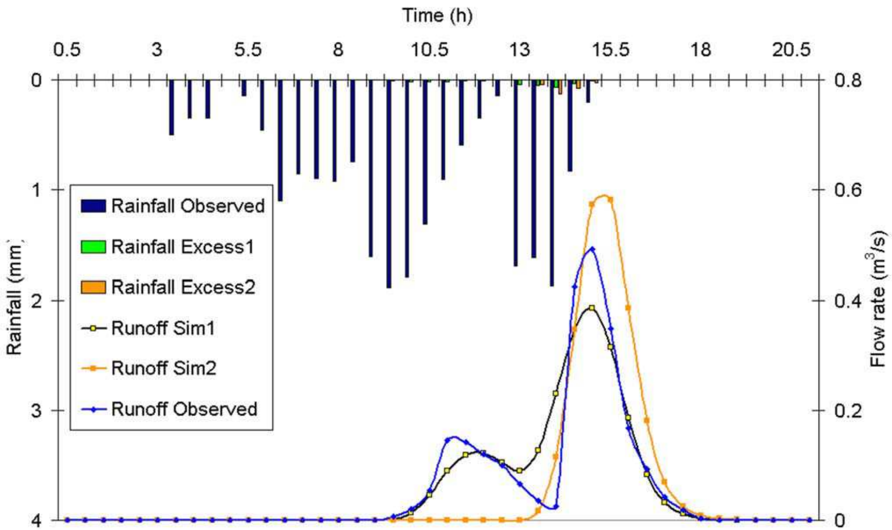

Fig. 9. Storm event of 17 February 2007.

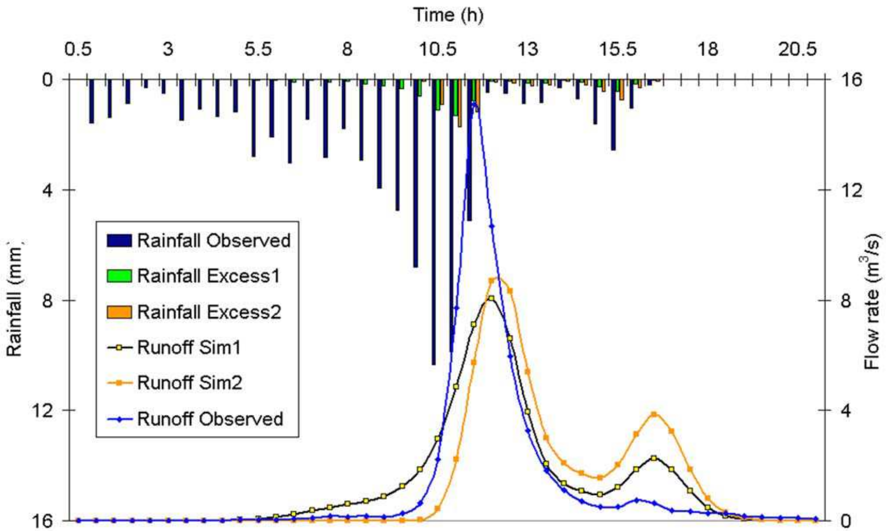

Fig. 10. Storm event of 23 November 2005.

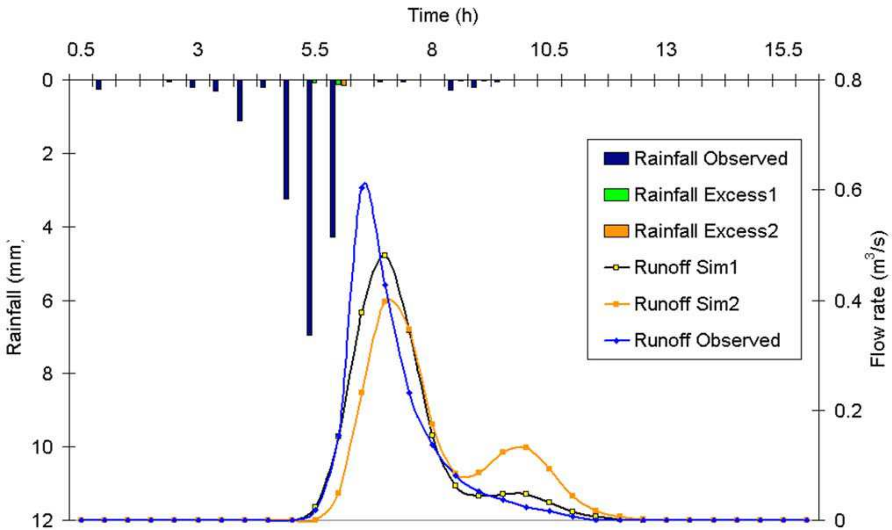

Fig. 11. Storm event of 8 November 2004.